

# Scaling patterns for the suppression of charged hadron yields in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV: Constraints on transport coefficients

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Suppression measurements for charged hadrons are used to investigate the path length ( $L$ ) and transverse momentum ( $p_T$ ) dependent jet quenching patterns of the hot and dense QCD medium produced in Pb+Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV at the LHC. The observed scaling patterns, which are similar to those observed for Au+Au collisions at  $\sqrt{s_{NN}} = 0.20$  TeV at RHIC, show the trends predicted for jet-medium interactions dominated by radiative energy loss. They also allow a simple estimate of the transport coefficient  $\hat{q}$ , which suggests that the medium produced in LHC collisions is somewhat less opaque than that produced at RHIC, if the same parton-medium coupling strength is assumed. The higher temperature produced in LHC collisions could reduce the parton-medium coupling strength to give identical values for  $\hat{q}$  in LHC and RHIC collisions.

During the early stage of a relativistic heavy ion collision, quarks and gluons are often scattered to large transverse momentum  $p_T$ . These scattered partons can interact and lose energy as they traverse the short-lived quark-gluon plasma (QGP), also produced in the collision [1]. The scattered partons which subsequently emerge, fragment into topologically aligned high- $p_T$  hadrons or jets; their suppressed yields encode the degree of parton energy loss. This essential consequence of parton energy loss has been characterized at the Relativistic Heavy Ion Collider (RHIC), via the observation that high- $p_T$  hadron yields are suppressed in central and mid-central AA collisions, in comparison to the binary-scaled yields from p+p collisions [2, 3]. The magnitude and trend of this suppression – termed “jet quenching” – has been a key ingredient in recent attempts to estimate the transport properties of the QGP [4–14].

The Large Hadron Collider (LHC) has now extended the available c.m. energy range for AA collisions by more than a factor of ten, enabling investigations of the energy loss of much more energetic partons in the QGP medium produced at a higher temperature [15–18]. Relative to Au+Au collisions at RHIC ( $\sqrt{s_{NN}} = 0.2$  TeV), the measured multiplicity for Pb+Pb collisions at the LHC ( $\sqrt{s_{NN}} = 2.76$  TeV) suggests an approximately 30% increase in the temperature of the QGP medium. This increase in temperature could result in a lowering of the strong interaction coupling strength, as well as a change in the stopping power of the medium. Either could have a significant influence on the magnitude of parton energy loss, which in turn, influences the magnitude and trend of jet quenching. Thus, an important open question is the extent to which jet quenching measurements differ at RHIC and the LHC, and whether a characterizable difference gives an indication for the expected change in the properties of the medium created in LHC collisions.

An experimental probe commonly used to quantify jet quenching in AA collisions is the nuclear modification

factor ( $R_{AA}$ );

$$R_{AA}(p_T) = \frac{1/N_{\text{evt}} dN/dy dp_T}{\langle T_{AA} \rangle d\sigma_{pp}/dy dp_T},$$

where  $\sigma_{pp}$  is the particle production cross section in p+p collisions and  $\langle T_{AA} \rangle$  is the nuclear thickness function averaged over the impact parameter ( $\mathbf{b}$ ) range associated with a given centrality selection

$$\langle T_{AA} \rangle \equiv \frac{\int T_{AA}(\mathbf{b}) d\mathbf{b}}{\int (1 - e^{-\sigma_{pp}^{inel} T_{AA}(\mathbf{b})}) d\mathbf{b}}.$$

The average number of nucleon-nucleon collisions,  $\langle N_{coll} \rangle = \sigma_{pp}^{inel} \langle T_{AA} \rangle$ , is usually obtained via a Monte Carlo Glauber-based model calculation [19, 20].

The  $R_{AA}$  measurements for neutral pions ( $\pi^0$ ) produced in RHIC collisions ( $\sqrt{s_{NN}} = 0.2$  TeV), show a characteristic dependence on both  $p_T$  and the estimated path length  $L$  of the medium. More specifically,  $\ln[R_{AA}(p_T, L)]$  has been observed to scale as  $L$  and  $1/\sqrt{p_T}$  respectively (*i.e.*  $\ln[R_{AA}(p_T, L)]$  shows a linear dependence on  $1/\sqrt{p_T}$  for fixed values of  $L$ , and a linear dependence on  $L$  for fixed values of  $p_T$ .) [6]. These scaling patterns reflect the predicted quenching of the transverse momentum spectrum for jets produced from scattered light partons which lose energy via medium induced gluon radiation [21];

$$R_{AA}(p_T, L) \simeq \exp \left[ -\frac{2\alpha_s C_F}{\sqrt{\pi}} L \sqrt{\hat{q} \frac{\mathcal{L}}{p_T}} \right]$$

$$\mathcal{L} \equiv \frac{d}{d \ln p_T} \ln \left[ \frac{d\sigma_{pp}}{dp_T^2}(p_T) \right], \quad (1)$$

where  $\alpha_s$  is the strong interaction coupling strength,  $C_F$  is the color factor and  $\hat{q}$  is the transport coefficient which characterizes the squared average transverse momentum exchange [per unit path length] between the medium and the parton.

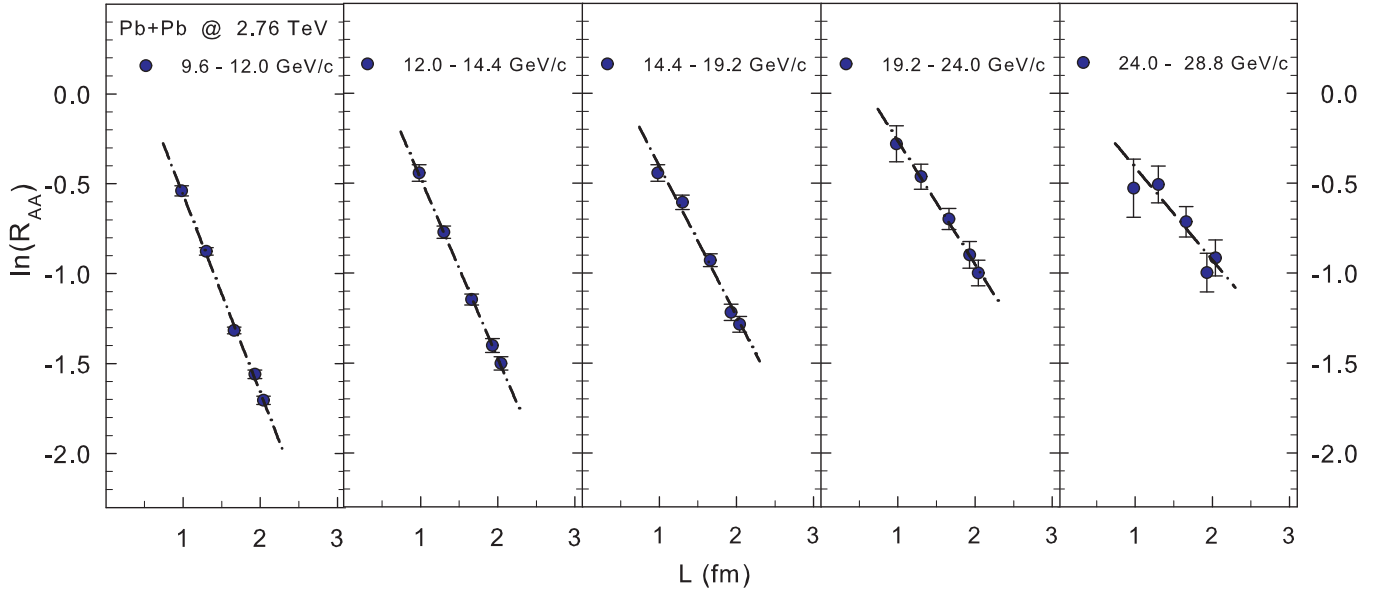


FIG. 1. (Color online)  $\ln[R_{AA}(p_T, L)]$  vs.  $L$  for several  $p_T$  selections as indicated. Error bars are statistical only. The dot-dashed curve in each panel is a linear fit to the data (see text).

The excellent agreement between the scaling patterns observed for the RHIC  $R_{AA}$  data and those predicted by Eq. 1, has been interpreted as an indication that medium induced gluon radiation dominates the underlying mechanism for jet quenching in RHIC collisions [6]. The slopes of these scaling curves, which encode the magnitude of  $\alpha_s$  and  $\hat{q}$  (cf. Eq. 1), have also been used to extract a simple estimate of  $\hat{q}$  for the medium produced in these collisions [6].

A fundamental change in the mechanism for jet quenching is not expected as the beam energy is raised from  $\sqrt{s_{NN}} = 0.2$  (RHIC) to  $\sqrt{s_{NN}} = 2.76$  TeV (LHC). Thus, the scaling patterns observed for RHIC  $R_{AA}$  data, might also be expected at the higher beam collision energy. We therefore search for these scaling patterns in LHC  $R_{AA}$  data, with an eye towards a possible difference in the slopes of the scaling curves for the two beam energies. Such slope differences could signal a change in the properties of the medium created in LHC collisions.

The  $R_{AA}$  measurements employed in our search were recently reported for charged hadrons by the CMS collaboration [17]. These data and their associated errors, are shown as a function of  $p_T$  for several centrality selections in Fig. 4 of Ref. [17]. They indicate that suppression is modest in peripheral collisions, but is increasingly pronounced in more-central collisions, as might be expected from the longer path lengths associated with central and mid-central collisions (cf. Eq. 1). They also indicate that  $R_{AA}$  reaches a centrality dependent minimum value for  $p_T \approx 6 - 7$  GeV/c, but shows a clear increase with  $p_T$  up to at least 40 GeV/c. These features provide the substance for the scaling search discussed below.

To facilitate comparisons to our earlier analysis of RHIC  $\pi^0$  data, we apply the cut  $p_T \gtrsim 10$  GeV/c for our scaling search. Here, it is noteworthy that RHIC measurements indicate that the  $R_{AA}$  values for neutral pions and charged hadrons converge for  $p_T \gtrsim 9$  GeV/c, [22, 23]. We also use the transverse size of the system  $\bar{R}$  as a simple estimate for the path length  $L$ , as was done in our earlier analysis. A Monte-Carlo Glauber-based model calculation [19, 20] was used to evaluate the values for  $\bar{R}$  in Pb+Pb collisions as follows. For each centrality selection, the number of participant nucleons  $N_{part}$ , was first estimated. Subsequently,  $\bar{R}$  was determined from the distribution of these nucleons in the transverse ( $x, y$ )

plane as:  $1/\bar{R} = \sqrt{\left(\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2}\right)}$ , where  $\sigma_x$  and  $\sigma_y$  are the respective root-mean-square widths of the density distributions. For these calculations, the initial entropy profile in the transverse plane was assumed to be proportional to a linear combination of the number density of participants and binary collisions [24, 25]. The latter assures that the entropy density weighting used, is constrained by the Pb+Pb hadron multiplicity measurements [26]. Averaging for each centrality, was performed over the configurations generated in the simulated collisions.

The main results from our scaling search are presented in Figs. 1 and 2. The plots of  $\ln[R_{AA}(p_T, L)]$  vs.  $L$  are shown for different  $p_T$  selections [as indicated] in the five panels shown in Fig. 1. Within errors, all of these plots show the linear increase with  $L$ , predicted in Eq. 1. This linear dependence is exemplified by the dashed-dot curves which represent linear fits to the data. The fits indicate an intercept  $L \approx 0.5 \pm 0.1$  fm (for  $\ln[R_{AA}(p_T, L)] = 0$ ),

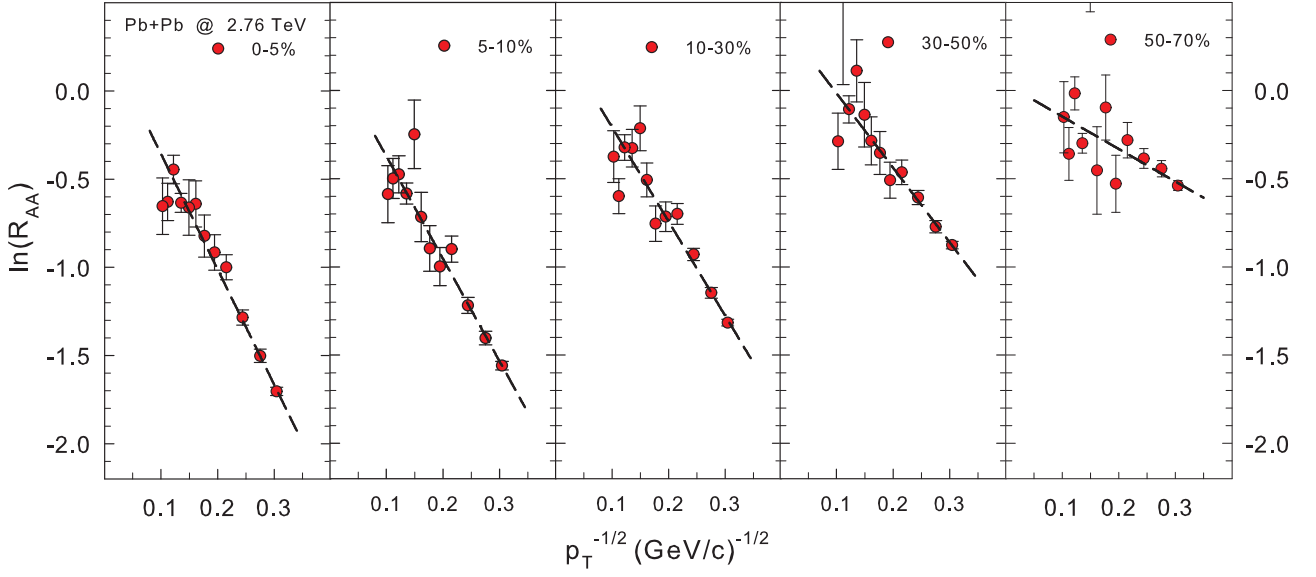


FIG. 2. (Color online)  $\ln[R_{AA}(p_T, L)]$  vs.  $1/\sqrt{p_T}$  ( $p_T \gtrsim 10$  GeV/c) for several centrality selections as indicated. Error bars are statistical only. The dashed curve in each panel is a fit to the data (see text).

which is similar to the value  $L \approx 0.6 \pm 0.1$  fm observed in RHIC collisions [6]. This suggests a similar minimum path length requirement for the initiation of jet quenching in RHIC and LHC collisions. Note that this requirement is akin to the plasma formation or cooling times proposed in Refs. [27, 28]. The slopes  $S_L$  of the curves in Fig. 1 also show a decrease with increasing  $p_T$  selection, indicating the expected mild decrease in jet quenching as  $p_T$  is increased (cf. Eq. 1).

The complimentary plots of  $\ln[R_{AA}(p_T, L)]$  vs.  $1/\sqrt{p_T}$  are shown in Fig. 2 for five separate centrality selections as indicated. In likeness to Fig. 1, all of these plots show the predicted linear decrease with  $1/\sqrt{p_T}$  (cf. Eq. 1); here, the dashed curves represent linear fits to the data. The extrapolated intercepts ( $\ln[R_{AA}(p_T, L)] = 0$ ) of these curves indicate that the linear decrease of jet quenching persists up to the relatively high value  $p_T \approx 800$  GeV/c in central collisions. The corresponding slopes  $S_{p_T}$  of these curves decrease as collisions become more peripheral, indicating the effects of the shorter path lengths that partons traverse as collision become more peripheral.

For a given medium (fixed  $\hat{q}$ ) Eq. 1 suggests that the ratio  $S_{p_T}/L$  should be independent of the collision centrality, and the product  $S_L\sqrt{p_T}$  should be independent of  $p_T$ . The flat centrality dependence shown for  $S_{p_T}/L$ , in Fig. 3, validates this prediction. Within errors, the product  $S_L\sqrt{p_T}$  shows a similarly flat  $p_T$  dependence for  $p_T$  values which allow reliable extraction of  $S_L$ . The magnitude of the values for  $S_L\sqrt{p_T}$  are also similar to those for  $S_{p_T}/L$ , as expected from Eq. 1. These observations all suggest the validity of Eq. 1. Therefore, we use the average value of these ratios and products to esti-

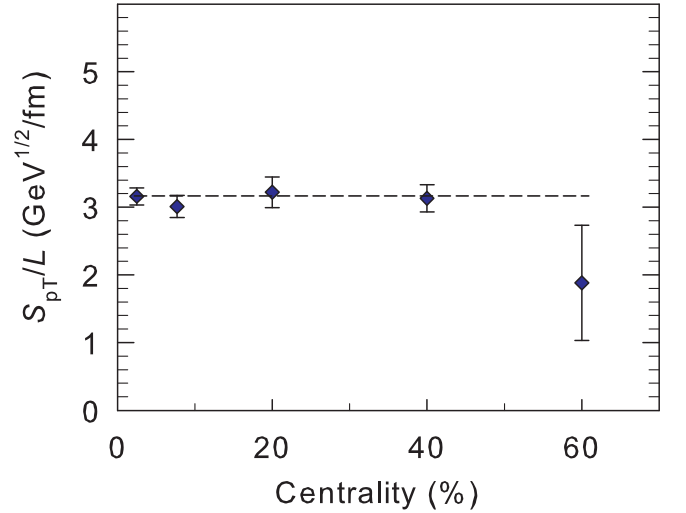


FIG. 3. (Color online) Centrality dependence of  $S_{p_T}/L$ , see text. The slopes  $S_{p_T}$  are obtained from the linear fits shown in Fig. 2. The dashed curve is drawn to guide the eye.

mate  $\hat{q}_{LHC}$  and compare it to the  $\hat{q}_{RHIC}$  value previously extracted with the same technique.

One can compare the values for  $\hat{q}$  at  $\sqrt{s_{NN}} = 0.2$  and 2.76 TeV as follows: First, we average the values of  $S_{p_T}/L$  and  $S_L\sqrt{p_T}$  to obtain the value  $3.3 \pm 0.15$  GeV<sup>1/2</sup>/fm. Then using Eq. 1 with values of  $\alpha_s = 0.3$  [5],  $C_F = 9/4$  [21, 29] and  $\mathcal{L} = n = 6.7$  [30], one obtains  $\hat{q}_{LHC} \approx 0.56 \pm 0.05$  GeV<sup>2</sup>/fm. This estimate of  $\hat{q}_{LHC}$ , which can be interpreted as a space-time average, is approximately 25% smaller than our earlier estimate of  $\hat{q}_{RHIC} \approx 0.75 \pm 0.05$  GeV<sup>2</sup>/fm, evaluated with the same values for  $C_F$  and  $\alpha_s$  [6]. Thus, the QCD medium

produced in LHC collisions, seems to be somewhat less opaque to partons than the medium produced at RHIC, if a fixed value of the parton-medium coupling strength is assumed [14]. However, since the exponent of Eq. 1 varies as  $\alpha_s \sqrt{\hat{q}}$ , it is the product  $\alpha_s^2 \hat{q}$  that is  $\sim 25\%$  smaller for  $\sqrt{s_{NN}} = 2.76$  TeV. Therefore, a small ( $\sim 12.5\%$ ) thermal suppression of  $\alpha_s$  would lead to identical magnitudes for  $\hat{q}_{LHC}$  and  $\hat{q}_{RHIC}$ . We conclude that the value of the transport coefficient  $\hat{q}$ , is very similar for the hot and dense medium created in RHIC and LHC collisions, although a possible change in  $\alpha_s$  has not been independently established. The close similarity between  $R_{AA}$  measurements at RHIC and the LHC is a good indicator that  $\hat{q}_{LHC}$  and  $\hat{q}_{RHIC}$  are quite comparable.

In summary, we have performed validation tests of the scaling properties of jet suppression in Pb+Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. These tests confirm the  $1/\sqrt{\langle p_T \rangle}$  dependence, as well as the linear dependence on path length predicted by Dokshitzer and Kharzeev for jet suppression dominated by the mechanism of medium-induced gluon radiation in a hot and dense QGP. The quenching patterns indicate a minimum path length requirement for the initiation of charged hadron suppression, but suggest that jet quenching extends up to a relatively high value of  $p_T$  in central collisions. For a fixed value of the coupling strength  $\alpha_s$ , the QCD medium produced in LHC collisions appears to be less opaque to partons than at RHIC. However, a small ( $\sim 12.5\%$ ) thermal suppression of  $\alpha_s$  would lead to the same magnitude for  $\hat{q}_{LHC}$  and  $\hat{q}_{RHIC}$ . Such a suppression might result from the approximately 30% growth in the temperature of the QGP medium produced in LHC collisions. The extracted values for  $\hat{q}_{LHC}$  and  $\hat{q}_{RHIC}$  are comparable to the recent estimates of  $\sim 1 - 2$  GeV<sup>2</sup>/fm obtained from fits to hadron suppression data within the framework of the higher twist (HT) expansion [12, 31] and the Gyulassy-Levai-Vitev (GLV) scheme [14, 32]. However, they are much smaller than the value extracted via the approach of Arnold, Moore and Yaffe (AMY) [5, 33] and that of Armesto Salgado and Wiedemann (ASW) [5, 8]. These results should provide important model constraints in ongoing attempts to use jet-quenching as a quantitative tomographic probe of the QGP.

## ACKNOWLEDGMENTS

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